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On the mixed mode I/II fracture properties of jute fiber-reinforced concrete

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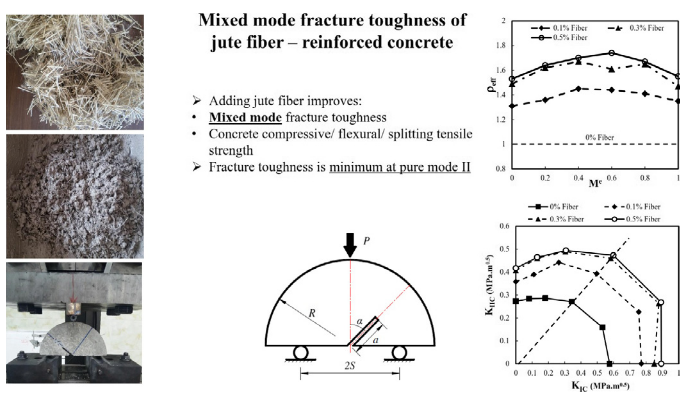
HIGHLIGHTS

- Adding jute fibers improves mixed mode fracture toughness of concrete.
- Minimum fracture toughness of jute fiber-reinforced concrete occurs at mode II.
- Jute fibers enhances compressive, tensile, and flexural strengths of concrete.

GRAPHICAL ABSTRACT



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ABSTRACT

In this paper, mixed mode I/II fracture toughness of jute fiber-reinforced concrete is investigated experimentally using a large number of cracked semi-circular bend (SCB) specimens. For this purpose, jute fibers with percentages of 0.1%, 0.3%, and 0.5% by weight and of 20 mm length are used to be mixed with plain concrete. Cracked semi-circular bend (SCB) specimens are employed to obtain fracture toughness under mixed mode I/II loading conditions from pure mode I to pure mode II. The results show that the effects of the fiber percentages on the mixed mode fracture toughness is very significant. It is found that specimens made of jute fiber-reinforced concrete represent higher resistance against crack growth than those of made of plain concrete. The compressive strength, splitting tensile strength and flexural strength of the concrete mixes is also studied. It is shown that jute fiber improves compressive, splitting tensile, and flexural strength of concrete materials.

1. Introduction

Concrete is the most widely used construction material, because of the some well-known benefits it offers, such as low cost, wide applicability, and general availability. As a quasi-brittle material, generally, concrete gets more brittle as its strength increases. However, relatively low tensile strength and poor resistance to crack growth are among the major disadvantages of plain concrete [1].

Admittedly, adding fibers to concrete mixtures improves the energy absorption capacity and cracking resistance of the plain concrete [2–4]. By bridging fibers across the cracks in fiber reinforced concrete, a post-cracking ductility is attained, and consequently, the toughness of concrete is remarkably improved.

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Nomenclature

a	crack length	P_{cr}	critical applied load
H.O.T	higher order terms	r, θ	polar coordinate components
K_{eff}	effective stress intensity factor	R, t	radius and thickness of the SCB specimen
K_I, K_{II}	mode I and II stress intensity factors	S	location of loading supports
K_{IC}, K_{IIC}	mode I and II fracture toughness	SCB	cracked semi-circular bend specimen
K_{If}, K_{IIf}	mode I and II stress intensity factors corresponding to the fracture load	Y_I, Y_{II}	mode I and II geometry factors
M^e	mode mixity parameter	α	crack inclination angle
P	applied load	σ_{ij} ($i,j \equiv r,\theta$)	crack tip stress components in polar coordinates
		ρ_{eff}	relative mixed mode fracture toughness

Fracture toughness of a material determines the energy absorption capacity and the cracking resistance, and hence, is vital to be evaluated for design purposes [5].

Natural fibers which are biodegradable, affordable, green, and accessible [6], are obtained from naturally available resources such as coconut tree, banana tree, cotton, and jute. Researchers have conducted various studies on the impact of natural fibers on the mechanical and physical behavior of concrete to investigate the extent of improvement. In recent years, extensive studies have been done on the effects of natural fibers in fiber reinforced concrete composites (FRCC) in terms of strength, energy efficiency, and the impact resistance [7–10]. The demands to incorporate natural fibers for producing high-quality and low cost sustainable FRCC for housing and other necessities are increasing. Other potential application of natural fiber-reinforced cement composites are areas where energy needs to be absorbed or those areas prone to impact damage. Accordingly, natural fiber-reinforced cement composites are mostly applicable for shatter- and earthquake-resistant construction, foundation floor for machinery in factories, fabrication of lightweight cement-based roofing and ceiling boards, wall plaster, and construction materials for low-cost housing [11]. Various factors influence mechanical properties of FRCC reinforced with natural fibers. Among them are characteristics of fibers, nature of the cement-based matrix, mixing procedure, casting, and curing conditions of the composite [11]. The type of fiber and their characteristics are among the most important factors that have crucial effects on the mechanical properties of these composites [12]. Ramakrishna and Sundararajan [13] tested sisal, coir, jute and *Hibiscus cannebinus* (kenaf) fibers reinforced cement mortars with different fiber lengths and fiber dosages to investigate impact resistance of mortars. They found that the impact strength of mortars with fiber reinforcement is always higher than that of those without fiber reinforcement. Kundu et al. [14] reported a cost effective process methodology for manufacturing jute fiber reinforced concrete sewage pipe. In that study, jute fibers were chopped and treated by chemicals in order to achieve homogeneous dispersion of jute fibers into cement matrix. It was found that the load bearing capacity of jute fiber-reinforced sewage pipes was significantly increased as compared to the concrete pipes made without fiber reinforcement, indicating that natural fibers, such as jute fibers, could be reasonably good reinforcement for cement-based materials. Kaushik et al. [15] studied the flexural and impact strength of Jute fiber reinforced epoxy/polyester composites and reported a considerable enhancement as a result of adding jute fiber.

Jute fibers, which come from annual plants, are available in plenty and hence, can be considered as a prospective material for cement-based composites. According to Kundu et al. [16], jute fibers are about seven times lighter than steel fibers and provide a suitable tensile strength of 250–300 MPa. The effect of short discrete jute fibers on the failure and impact properties of cementitious composites is also investigated by Zhou et al. [9]. According to them, adding jute fibers improves strength, impact resistance, and cracking resistance of the concrete. Such studies imply that jute fibers can be a considered as a proper replacement of the traditional fibers in concrete materials.

Fracture mechanics is widely used as a requisite tool to prevent and predict catastrophic failures of man-made structure such as cement-based materials. Brittle fracture is one of the frequent modes of failure in engineering materials. Since material defects such as crack sand flaws have a significant role in the processes of brittle fracture, fracture mechanics investigates the mechanical behavior of cracked components from various aspects. Linear elastic fracture mechanics (LEFM) deals with the conditions in which the amount of plastic deformation around the crack tip is not considerable with respect to the crack length, and as a result, stress and strain fields can be represented in the form of linear elastic solutions. This concept has successfully been applied to many brittle and quasi-brittle materials to predict mixed mode fracture behavior of the materials under combined tensile – shear loading [17–22]. For example, Mirsayar et al. studied the mixed mode fracture behavior of polycrystalline graphite using a tangential strain based criterion, developed in LEFM framework. The concept of LEFM has also been widely applied to cement mortar and concrete by many researchers [17,23–27]. Carpinteri [25] studied a relationship between tensile strength of concrete and mixed mode crack propagation by taking into account the size effects. He pointed out that the influences of heterogeneity and cohesive crack tip forces disappear by increasing the size-scale, and crack branching can be explained by the linear elastic stress field in vicinity of the crack tip. Mirsayar and Park [17], demonstrated that mixed mode fracture behavior in cement mortar can be addressed by a criterion, called extended maximum tangential stress criterion (EMTSN), which states that crack propagates in cement mortar in direction where the tangential strain reaches its ultimate value. As an example for fiber-reinforced concretes, Carpinteri and Brighenti [26] investigated effects of different values of the water/cement on the mixed mode fracture resistance, and other mechanical characteristics. However, the fracture behavior of natural fiber reinforced concrete has rarely been studied so far. A literature review reveals that the fracture toughness of natural fiber reinforced concrete is only investigated under pure mode I conditions [9,27,28]. However, a real structure made of concrete is subjected to combined tensile – shear loading during its service life. Therefore, the study of the fracture toughness of the natural fiber reinforced concretes under mixed mode loading is of great importance.

Several fracture test specimens are employed by the researchers in the past to evaluate mixed mode fracture toughness of different materials under mixed mode conditions. Among them, the specimens of circular or semi-circular shape are very suitable for fracture testing, cover all mixed mode conditions from pure mode I to pure mode II, and can be manufactured easier than other specimen types. The centrally cracked Brazilian disk (BD) specimen and the semi-circular bend (SCB) specimen are among the well-known